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Decarbonising domestic heating: What is the peak GB demand?

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ABSTRACT

Around 80% of domestic heat demand in Great Britain (GB) is supplied by natural gas, but continuing to heat dwellings in this way is unlikely to be compatible with national emission reduction targets. Electrical heating using heat pumps is expected to play a significant role in future space heating and hot water provision. The assessment of future heating technologies requires knowledge of the current demand for heat at short time intervals in order to evaluate peak demands and possible storage requirements. Existing half-hourly national heat demand estimates are built on data from small samples of dwellings. This paper provides estimates of GB domestic heat demand under mild, normal and cold weather conditions based on data from over 6000 dwellings collected between May 2009 and July 2010 that participated in the GB smart meter trial. The calculated peak domestic heat demand of 170 GW is around 40% lower than previously calculated suggesting that the difficulties surrounding the electrification of heat are far less profound than previously assumed. These results can be used in the development of future energy pathways and scenarios.

1. Introduction

In the UK,[1] household energy use is responsible for more than a quarter of national greenhouse gas emissions (Palmer and Cooper, 2013) and 75% of household energy use is for space and water heating. Given the national target to reduce GHG emissions to below 80% of the 1990 emissions by 2050 (BEIS, 2017a), significant reductions in the emissions from the domestic sector are expected.

Continuing to provide around 80% of UK domestic heat demand by natural gas is incompatible with emission reduction targets, unless very large improvements are made in building fabric efficiency. It is likely that emission reductions will be achieved through a combination of increased building efficiency and switching to lower CO_2 forms of heating (BEIS, 2017a, p. 77).

Decarbonisation of UK electricity generation and a shift to more electric heating is anticipated, although the extent of this is uncertain (BEIS, 2017a, p. 77). For example, in six scenarios produced independently by Department of Energy and Climate Change (DECC), the Committee on Climate Change, the Energy Technologies Institute, National Grid, the UK Energy Research Centre and Delta EE, the proportion of heat demand which was electrified ranged from 30% to 75% (Leveque and Robertson, 2014).[2]

The biggest challenge associated with greater use of heat pumps, or indeed any form of electric heating, is the increase in the peak demand in cold weather (Eyre and Baruah, 2015; DECC, 2012). The absolute increase in the demand for electricity, and the need to instantaneously balance supply and demand even when demand changes rapidly, are significant challenges. Whilst these could be solved by a substantial increase in generating capacity and the introduction of electrical storage, both are expensive. Understanding the scale of these challenges and the need for additional generation or storage requires knowledge of heat demand over short time intervals (e.g. half-hourly), in order to estimate likely peak demand and maximum rate of change of demand (ramp rate).

The total daily gas and electricity demand is available for Great Britain (GB), for example as illustrated in Fig. 1. Total daily GB gas demand may be divided into Daily Metered (large gas users only) and Non-Daily Metered (NDM). Approximately two thirds of NDM gas use is for domestic space and water heating, the rest being used in small non-domestic premises and for other purposes (Wilson et al., 2013). It is clear that the seasonal variations, as well as the absolute demand for domestic gas alone are greater than for total GB electricity demand.

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[1] The United Kingdom (UK) consists of Great Britain (GB) and Northern Ireland (NI), which has 2.9% of the UK population. GB is of primary interest in this paper, however occasional use is made of UK data when GB statistics are not available.

[2] Leveque and Robertson (2014) refer to personal correspondence in defining these scenarios, and in some cases refer to multiple documents about the same scenario. Readers are therefore referred to Leveque and Robertson rather than the multiple documents they reference.

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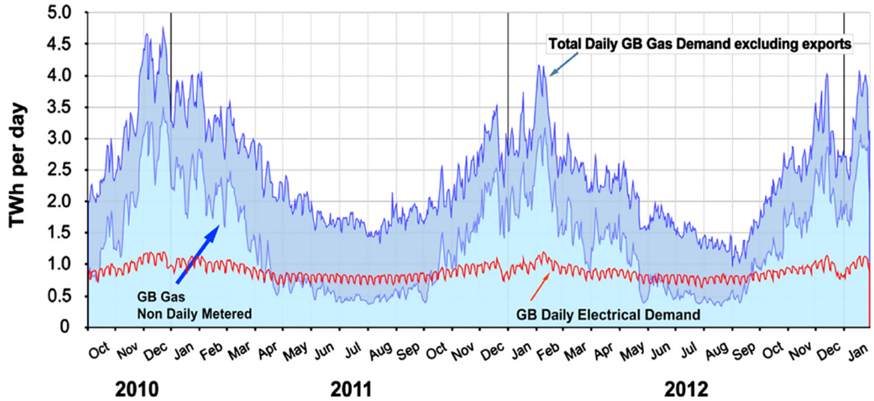

Fig. 1. Total daily GB gas use, total NDM gas use and electricity use, 29th September 2010 – 28th January 2013. (Source: Wilson et al., 2013).

Wilson et al. (2013) found that if 30% of NDM gas demand was replaced by direct electric resistance heating, the maximum daily electricity demand would be doubled, whereas with well-performing heat pumps (COP = 3) the daily maximum electricity demand would increase by 25%. However, as Wilson et al. emphasise, their analysis considers only daily demand, and since there is significant diurnal variation in the demand for heat, the instantaneous peaks could be much higher. Others have also explored future heating scenarios by assuming that heat demand is constant over 24 h but varies between days (Barton et al., 2013; Eyre and Baruah, 2015), or by making simple assumptions about the way that demand varies over the course of a day (Quiggin and Buswell, 2016; Sansom and Strbac, 2012). The credibility of such scenarios rests on the reliability of the modelled sub-daily demands for domestic heat.

To provide an estimate of the likely peak demands and ramp rate, Sansom (2014) synthesised the GB combined domestic and non-domestic space and water heat demand at half-hourly intervals for 2010, which was a particularly cold year (Fig. 2). To do this he firstly obtained the daily heat demand from a segmented regression with outdoor air temperature using GB gas demand statistics and then spread this into half-hourly values using profiles obtained from the monitoring of 19 condensing gas boilers and 52 micro-CHP systems between October 2006 and March 2007. This was a period without particularly cold weather (Sansom and Strbac, 2012). Different profiles were used for weekdays and weekends, but the same half-hourly demand profile was used for all weather conditions (i.e. the relative demands at each half hour were constant but the absolute values were scaled to reproduce the measured daily total demand). The total peak gas demand produced by this approach was 380 GW (Fig. 2), the peak for domestic heat only being 277 GW[3] (Sansom, 2017). The variation in demand (ramp rate) was more than 120 GW over the course of an hour. For comparison, the peak daily NDM gas demand shown in Fig. 1 of 3.5 TWh would equate to a mean power of 145 GW, which is clearly much lower than the half-hourly peak of 277 GW estimated by Sansom. Although the quantities considered by Sansom, and NDM gas demand, are not quite the same thing,[4] this nevertheless shows the importance of variations within a day in determining peak demand for heat. Sansom's graph has proven to be rather influential and is widely quoted (e.g. DECC, 2012; Energy Technologies Institute, 2015; Maclean et al., 2015; Chaudry et al., 2015; Howard and Bengherbi, 2016), so the reliability of Sansom's figures, and any values extracted from it, is worth careful investigation.

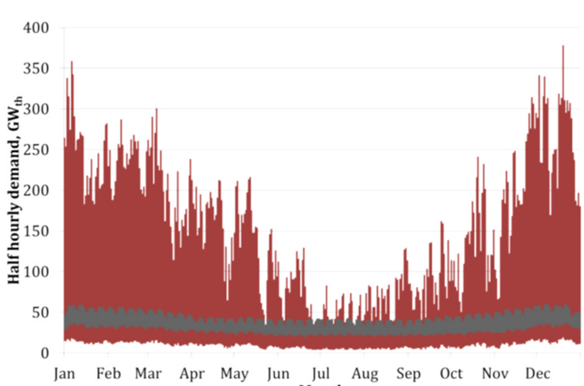

Fig. 2. Synthesised GB half-hourly domestic and non-domestic heat demand for January to December 2010 and actual GB electricity demand. Source: Sansom (2014).

In this paper, a more robust method is used to estimate the half-hourly GB domestic space and hot water heat demand. Half-hourly gas data from more than 6000 homes, measured over a 15-month period (May 2009 to July 2010), is extended to the national stock using a simple model to account for the impact on demand of both weather and the socio-demographics of the GB population. The dataset contains around 100 times more dwellings than the dataset used by Sansom, and includes cold weather, giving a much more reliable estimate.

The estimates of GB domestic heat demand obtained here differ from previous work in three main ways: they are based on a much larger sample of homes, the monitoring period included particularly cold weather, and the model takes account of the way the heat demand profile shape varies with outdoor temperature. The predictions of annual demand, half-hourly profiles, peak demands and ramp rate are compared to the results of Sansom and other known values. The conclusions drawn, and the demand profiles generated, are particularly useful for future energy scenario modelling, as they provide a more reliable estimate of half-hourly GB domestic heat demand than has been previously available.

2. Selecting and cleaning the dataset

2.1. The EDRP data

The Energy Demand Research Project (EDRP) involved separate studies carried out by four energy suppliers (EDF, SSE, EON and

[3] Elsewhere a peak of 304 GW is quoted (Energy Technologies Institute, 2015) for domestic heat demand, referenced to Sansom. The reason for this difference from the peak of 277 GW supplied by Sansom to the lead author of this paper is due to an error either in the data supplied to the ETI or to the lead author of this paper (Sansom, 2017).

[4] NDM gas demand, as used by Wilson et al., includes certain non-domestic uses of gas such as agriculture and small commercial and industrial users, but does not include domestic heating which is not gas-fired (e.g. electric or oil). Sansom's graph includes domestic space and water heating of all types but not non-domestic heating.

Scottish Power) between 2007 and 2010 (AECOM, 2014). The original purpose was to investigate the effect of various forms of non-physical interventions on households' energy use, for example, information on current and past consumption, the setting of energy targets, provision of advice and financial incentives, benchmarking and a competition.

There were 8700 dwellings involved in the trials that had smart meters measuring half-hourly gas consumption. This included the gas used for space and water heating as well as for other purposes, notably cooking. (Around 2% of UK domestic gas demand is used for cooking (BEIS, 2017b)). This is currently the largest publicly-available GB dataset that includes gas readings at sub-daily resolution. (The only other comparable data set is the Irish Smart Meter Gas Trial, which included 1500 dwellings (Quiggin, 2014)).

In addition to the half-hourly gas demand, the Acorn type and the approximate location of the dwellings is given. Acorn is a proprietary socio-demographic segmentation tool that is based on a range of sources, including government data, and is given at postcode level (Acorn, 2014). It divides postcodes into six *Categories,*[5] designed to reflect the kinds of people who live in an area, their attitudes and how they behave. Location is given by the NUTS4[6] (now LAU1), Local Authority[7] and Local Distribution Zone (LDZ). The LDZs, which are important for defining the dwelling location in this work, are used by the National Grid for gas demand estimation and other purposes. There are 13 LDZs for gas in GB.

No other information on the dwellings is provided, i.e. about their type, construction, energy system or tenure. It is not stated which energy supplier monitored which dwelling and whether the gas demand data is from before or after an intervention. However, none of the interventions changed the total energy demand of any dwelling by more than 5% (Raw et al., 2011). Slightly different recruitment methods were used by the four different energy suppliers (Raw et al., 2011), although in general the aim was to ensure a typical sample of homes, excluding homes which were likely to be unusual (e.g. homes of employees of the energy company).

By the end of the EDRP trial, the data logging process was almost 100% effective, but initially all the energy suppliers had "major issues" with processing and managing data from the smart meters. No indication is given by Raw et al. as to when the data became reliable.

Considerable effort was directed towards creating an error free and unbiased sub-sample from the EDRP data set which could be used, herein and by others, to calculate the national heat demands. The process is explained fully here and supported by Supplementary information (Watson et al., 2018), so that any weaknesses and biases in the data set can be discerned.

2.2. Data processing and cleaning

In order for the analysis to have value, it was necessary to have a consistently large sample size with no significant data errors or breaks in the data, and for the statistical analysis purposes, it was desirable that the number of dwellings yielding clean, complete, half hourly gas values was constant on any given day (although the number of dwellings was allowed to change between the end of one day and the start of the next.)

The daily sample size climbed rapidly from near zero to around 5500 between 1st May 2008 and 1st August 2008 (Fig. 3), it remained between 5500 and 6000 from 1st August 2008 to 1 st April 2009, and then increased to around 7600 dwellings. At the beginning of August 2010, the daily mean sample size dropped substantially, from around 5700 to around 1800. On average, each dwelling had 585 days of data.

The sample size actually varied at each half hour, due to dwellings leaving and joining the sample, and due to missing data. This is shown in Fig. 3 by the difference between the daily minimum and daily maximum sample size, which is most obvious after 1st April 2009.

For this research, the data before 1st August 2008 and after 31st July 2010 was rejected because the sample size varied substantially day by day. To select the sample from within this period a three-stage process was adopted.

- Firstly, missing data was, where possible, replaced.
- Secondly, the period of time over which the data was reliable was selected.
- Thirdly, the dwellings producing erroneous data were identified and individual days of data or whole dwellings were removed from the sample.

The three-stage process, data patching, sample selection and error removal is summarised in Table 1, including the effect of each step in the process, see also Supplementary information Section 1 (Watson et al., 2018). Steps 1–5 involve rejecting or modifying data on particular days, whereas steps 6–8 involve rejecting all data from certain dwellings outright.

The period of reliable data was selected as being from 1st May 2009 to 31 st July 2010. After cleaning and patching procedures had been applied, the final sample varied in size from 6645 to 5187 dwellings, with a mean sample size of 6401 dwellings (see Fig. 3, "Cleaned, patched sample size").

3. Predicting the GB heat demand

A bottom-up statistical model was used to provide estimates of GB domestic half-hourly heat demand for space heating and domestic hot water (DHW), for periods outside the monitoring period, based on daily outdoor temperature. Estimates are provided for total heat demand, and for space heating and DHW demand separately. This type of model has been found by Heller (2002), Pedersen et al. (2008), and Sansom and Strbac (2012) to be suitable for predicting heat demand from large groups of dwellings on an hourly or half-hourly basis.

There are four parts to the model derived herein. Firstly, the GB daily gas demand per-dwelling is determined for each day from a regression equation that relates this demand to the effective outdoor air temperature (ET). The regression equation is created using the measured daily gas demand for the EDRP homes. However, there are two additional factors which add complication to this process: the EDRP homes are not spatially distributed across GB in the same way as the national housing stock, and the relative number of households in each Acorn classification within the EDRP sample differs from the proportions in the GB stock as a whole. Solutions to these difficulties are described below and in the Supplementary information, section 2.

Secondly, daily gas demand is separated into gas used for space heating, DHW and cooking. This is based on data from BEIS (2017b) and the relationship between DHW demand and outdoor temperature derived from SAP2012 (BRE, 2013). Additional details are in the Supplementary information, Section 3.

Thirdly, the daily gas demand is spread through the day to produce the half-hourly profile. This process takes account of the way that half-hourly heating profiles differ with ambient temperature, something that was not done in the work of Sansom (2014). Different profiles are used

[5] Category 6 is communal establishments such as care homes and prisons, which are not of interest in this work. Categories 1–5 are homes, and are of interest here. Acorn categories are further subdivided into *Groups* and *Types*. Whilst the occupants rather than the building are the main focus of Acorn, the type and tenure of the housing forms a part of the description of many *types*. The Acorn system was revised in 2011; the information provided in the EDRP metadata is from the pre-2011 system.

[6] The Nomenclature of Territorial Units for Statistics (NUTS) is a system of dividing EU countries into regions of various sizes. Originally there were five levels, NUTS1 to NUTS5 but in 2003, NUTS4 and NUTS5 were replaced by LAU1 and LAU2 respectively. There are 415 LAU1 regions in the UK.

[7] The Local Authority (LA) code given in the EDRP data is the district in the old ONS system, which was phased out in 2011. There are 391 LAs in the UK.

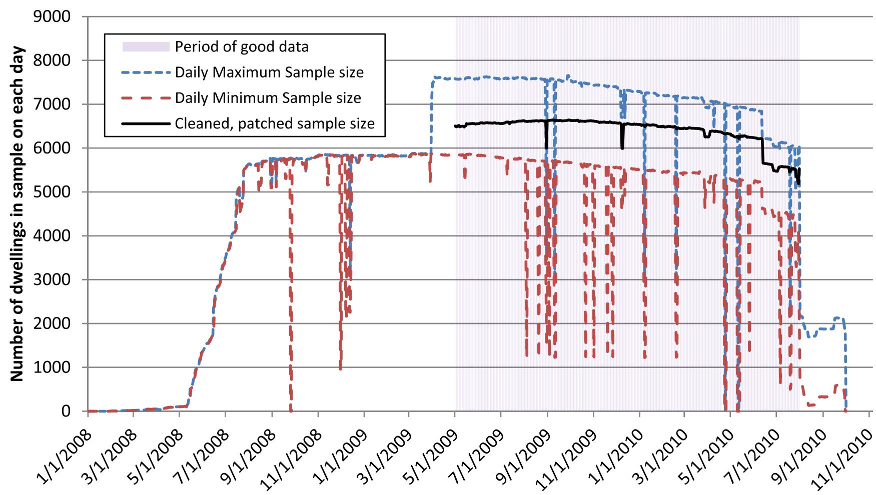

Fig. 3. Daily minimum sample size and daily maximum sample size 1st Jan 08–1 st Oct 10. The period of reliable data (1st May 09–31 st July 10) and the final cleaned and patch sample size during this period are shown.

Table 1
Summary of steps taken to obtain the clean, error free 15-month data sample.

Step	Procedure	Justification	Effect
Replacing missing data (see Supplementary Information S1.1)			
1	Replaced days where all dwellings were missing data using adjacent days of data.	Maintain continuity	9 days of data replaced for whole sample.
2	Filling the many missing readings at 01:00.	To ensure that all 48 half hours of data were present for every dwelling on each day, though the number of dwellings returning unbroken data changes day to day.	Average of 107 days per dwelling affected.
3	Replaced incomplete days of data using adjacent days, or removed if surrounding data not present.		Average of 18 days replaced and 2.6 days removed per dwelling.
Selecting the period of reliable data (see Supplementary Information S1.2)			
4	Identify the period of plausible data within the period from 1st August 2008–31st July 2010.	Before 1st May 2009, data found to be unreliable: implausible seasonal variation of Mean Load Factor (MLF) and Peak Coincidence Factor (PCF); weak correlation of demand and outdoor effective air temperature and unexplained peaks in demand.	Monitoring period reduced from 25 months to 15 months.
Identifying and removing implausible data (see Supplementary Information S1.3)			
5	Remove days with a half-hourly reading greater than 70 kW.	Maximum domestic boiler capacity usually 30 kW. Maintaining 70 kW for half an hour is unlikely	251 dwellings affected, on average 2.6 days of data removed from affected dwellings.
6	Reject dwellings with less than 20 days of data.	Dwellings with such small amounts of data add little value to the analysis.	752 dwellings removed.
7	Remove dwellings with greater than 15% (64) days of zero daily gas use.	These dwellings must have used other fuels for heating, or the data is in error.	883 dwellings removed
8	Remove dwellings where the correlation (R^2) between the effective outdoor air temperature and daily gas use is less than 0.4.	Some correlation between outdoor effective air temperature and daily gas demand expected. Most dwellings with $R^2 < 0.4$ had obviously spurious results.	388 dwellings removed

for total gas demand, DHW and space heating.

Fourthly, half-hourly gas demand for space heating, for DHW, and for both combined, is converted to heat demand.

In creating the model, no distinction is made between weekdays and weekends because treating weekdays and weekend days separately did not increase the accuracy of predictions. It proved important however, to use British Summer Time during summer rather than GMT.

Daily and annual gas demands are compared against official statistics for verification. Half-hourly results are compared against a portion of the original data which was reserved for this purpose.

3.1. Predicting half-hourly domestic gas demand

3.1.1. The GB daily domestic gas demand model

The regression model is based on plotting the daily heat demand per dwelling against the outdoor temperature. It was created using the EDRP data collected between 1st May 2009 and 31st July 2010, but with every tenth week of data removed for use in model verification. The detailed production of the model is complicated because the spatial and socio-demographic makeup of the sample is different to that of GB as a whole.

The X-axis in the regression is the *EDRP-weighted* mean daily effective outdoor air temperature (ET_{EDRP}). The daily temperature was obtained for each Local Distribution Zone (LDZ). These were weighted according to the proportion of the EDRP sample in that LDZ, in order to produce a single national value which was representative of the temperatures experienced by the dwellings in the EDRP sample. (The EDRP homes are predominantly located in just six of the 13 LDZs, see Fig. 4). The calculation of ET_{EDRP} is described in detail in the Supplementary Information, Section 2.1.

The Y-axis in the regression, the GB daily gas demand per dwelling, was weighted by Acorn category, in order to take account of differences in socio-demographics, building type, etc. between the EDRP sample and the GB housing stock. The mean daily gas demand per dwelling was obtained for each of the Acorn categories. These were combined to give a GB Acorn-weighted daily gas demand per dwelling by weighting the gas demand per dwelling for each Acorn category according to the proportion of GB households in that category (see Supplementary information, Section 2.2). The total GB domestic gas demand on any day is simply the Acorn-weighted gas demand per dwelling multiplied by

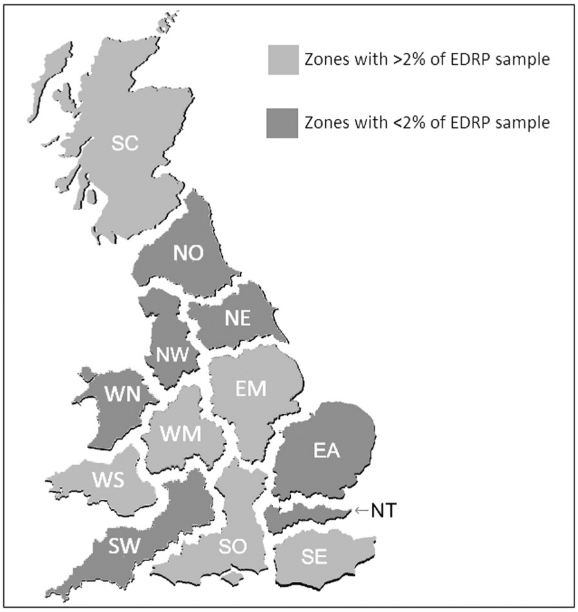

Fig. 4. Map of Local Distribution Zones in GB, showing those with more than 2% of the EDRP sub-sample.

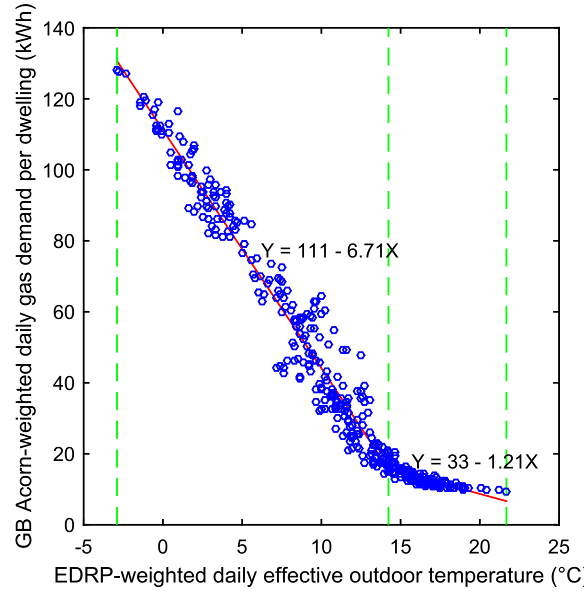

Fig. 5. Broken-stick regression of the Acorn-weighted daily gas demand per dwelling (EG) against the EDRP-weighted effective outdoor air temperature (ET_{EDRP}). The break-point is 14.2 °C and adjusted R^2 0.97.

the number of occupied dwellings in GB in that year, for example 25.5 million in 2010.

The EDRP-weighted effective temperature (ET_{EDRP}) was plotted against GB Acorn-weighted daily gas demand per dwelling (EG), for the 415 days of valid data, and a broken-stick regression line was fitted using an algorithm from Matlab (Hawkins, 1976). The regression coefficient, $R^2 = 0.97$, suggest that the demand/temperature relationship is robust. The automatically-obtained break point was at 14.2 °C. This indicates the average daily outdoor air temperature above which the space heating was no longer used in most of the EDRP dwellings, with gas being consumed in most, but not all, homes only for water heating and cooking. The breakpoint (also sometimes called the degree-day base temperature) is a little lower than the conventionally used value of 15.5 °C (Carbon Trust, 2017), which could reflect gradual improvements to the fabric energy efficiency of the GB stock.[8] The scatter around ET_{EDRP} values of 8–14 °C may be due to the relatively greater contribution of solar gains in the shoulder heating seasons, as well as occupant behaviour on mild, not cold days.

3.1.2. Obtaining total half-hourly gas demand profiles

Examination of the half-hourly load profiles for the Acorn-weighted gas demand per dwelling for the period from 1st May 2009 and 31st July 2010 suggested that the profiles differed with the external temperature in a systematic way. To investigate further, the EDRP-weighted mean daily effective outside air temperatures (ET_{EDRP}) were divided into eight 3 °C bands, −4.5 °C to −1.5 °C, −1.5–1.5 °C, …. 16.5–19.5 °C. The mean half-hourly GB Acorn-weighted gas demand (EG_{nat}) was then calculated for all the days within the same ET_{EDRP} band (Fig. 6, top), to get the half-hourly gas demand[9] for that temperature-band. These profiles were also normalised to give a daily demand of 1 (Fig. 6, bottom).

The profile of half-hourly gas demand clearly varies with

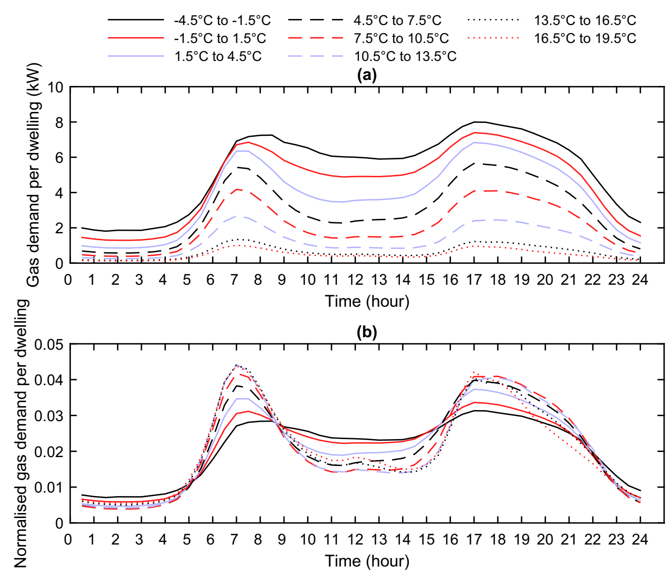

Fig. 6. Half-hourly gas demand per dwelling at mean daily outdoor effective temperatures (ET_{EDRP}) in 3 °C bands, in kW (a) and normalised to give daily demand of 1.0 (b).

temperature. As the days become colder, the demand reduction in the middle of the day is less marked, giving, an overall flatter profile, as illustrated by the normalised profile plot (Fig. 6, bottom). This may well be because some households choose to heat their home throughout the day when it is colder rather than using a two period-pattern. The overall effect is that the load factor decreases as the external temperature increases. (Load factor is the ratio of average demand to peak demand).

Therefore, when creating a model of half-hourly demand, it is important to account for the changes in the gas demand profile as the external temperature changes. This approach is quite different from that of Sansom (2014), who used the same profile shape for each weekday, and another profile for every weekend day, regardless of outdoor temperature.

[8] Sansom and Strbac (2012) fixed the cut-off temperature at 15.5 °C, rather than allowing the algorithm to find the optimal break-point automatically.

[9] The number of days used to produce each profile varied from three, temperatures (ET_{EDRP}) that occur infrequently (−4.5 to −1.5 °C), to 96 days for temperatures in the range from 13.5 °C to 16.5 °C.

To obtain GB half-hourly gas demand ($EG_{nat,d,t}$), the daily gas demand determined from the regression model (Fig. 5) was multiplied by the half-hourly normalised profile for the appropriate outdoor temperature band (Fig. 6, bottom), see Eq. (1). (The 2 in this equation is due to the conversion between GWh, and GW, given on a half-hourly basis).

$$EG_{nat,d,t} = 2 \times ND \times P_{t,b} \times \begin{cases} -6.71 \times ET_{NG,d} + 111, & for ET_{NG,d} < 14.1^{\circ}C \\ -1.21 \times ET_{NG,d} + 33, & for ET_{NG,d} > 14.1^{\circ}C \end{cases} \tag{1}$$

Where:

$EG_{nat,d,t}$ = predicted GB half-hourly domestic gas demand on day d at time t (GW)
ND = number of occupied dwellings in GB (millions).
$P_{t,b}$ = normalised half-hourly profile value, at time t, for temperature band b
$ET_{NG,d}$ = National Grid-weighted effective temperature on day d. (°C)
d = day
t = time (half hour)
b = temperature band.

3.1.3. Separation of total gas demand into space heating, DHW and cooking

The total gas demand was separated into demand for space heating, DHW and cooking. This was based on the observation that above a certain outdoor temperature, virtually all domestic gas demand will be for DHW and cooking. A new set of regression equations were developed to relate effective temperature to daily demand for space heating and DHW, and a new set of normalised profiles were used to convert these daily demands into half-hourly demands.

To account for the demand for cooking, it was assumed that 2% of annual domestic gas use is for this purpose (BEIS, 2017b), and that it is spread evenly through the year. This was subtracted from the Acorn-weighted daily total gas demand per dwelling, leaving only gas used for space heating and DHW.

To estimate the base-load for DHW, it is necessary to isolate those days on which there was no space heating. Based on the relationship between gas demand and outdoor temperature (See Supplementary information Section 3), and the results of Kane et al. (2015), it was assumed that above an ambient temperature of 18 °C all demand was for DHW; the mean gas demand on such days was taken as the DHW base-load.

As the ambient temperature decreases, the DHW heat demand increases above the base load because the temperature of the cold water supply decreases. To account for this, a linear relationship between outdoor temperature and the daily DHW heat demand was established based on monthly DHW values and outdoor temperatures from SAP2012 (BRE, 2013). This relationship enabled the rise in demand was over and above the base load for DHW be determined (Fig. 7).

Subtracting the cooking and daily DHW demand from the total leaves the gas demand for space heating only.

As before, daily gas demands were converted into half-hourly demands by multiplying by a normalised profile. The half-hourly DHW profile was taken to be the normalised mean half-hourly gas demand for all days with effective temperature over 18 °C. This profile shape was assumed not to vary with temperature.

To obtain the space heating normalised profiles, the DHW gas profile, scaled according to outdoor temperature, was subtracted from the total gas demand profile (minus the cooking demand) for that particular outdoor temperature, and then normalised. For further details, see Supplementary information section 3.

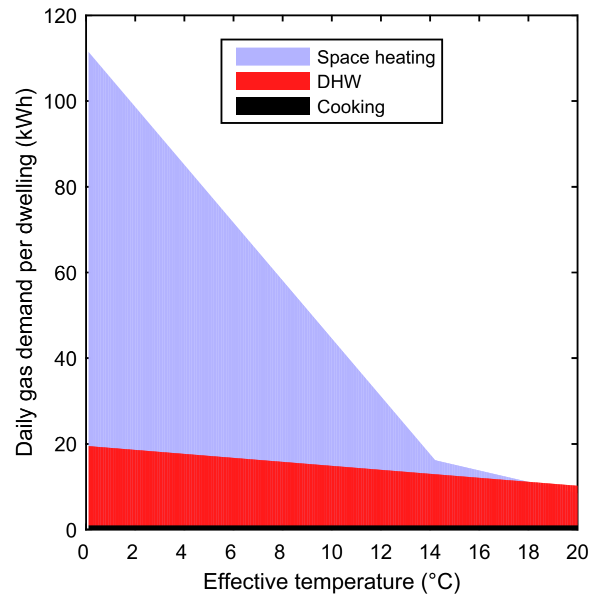

Fig. 7. Separating daily gas demand per dwelling into cooking, DHW and space heating demand.

3.2. Verification of daily, annual and half-hourly gas demands

Model results were verified in three ways: predicted daily gas demands were compared with daily GB NDM gas demand, half-hourly gas demands were compared against six weeks of EDRP data that was reserved for this purpose, and predicted annual gas demand for the UK was compared against UK official annual domestic gas demand statistics. In the case of official annual domestic gas demand statistics, it was possible to compare space heating and DHW demands separately.

A strong relationship ($R^2 = 0.93$) was found when actual daily NDM gas demand in 2015 (National Grid Data Item Explorer, no date) was plotted against the daily domestic gas demand predicted from the

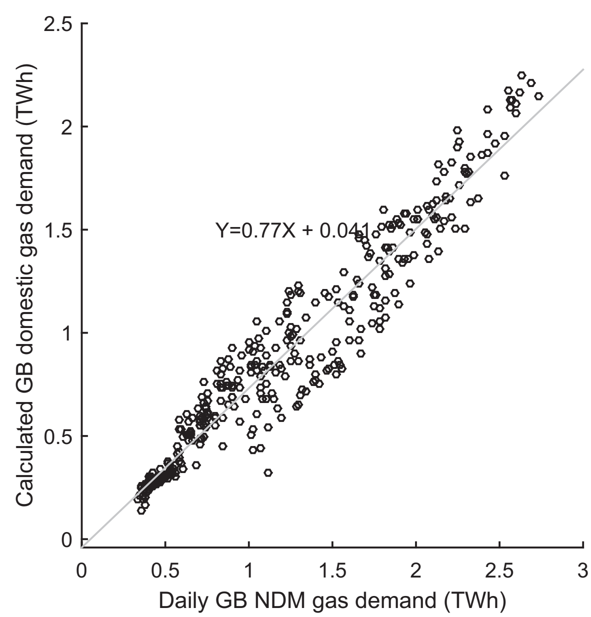

Fig. 8. Comparison of national daily non-daily metered (NDM) gas consumption and modelled daily domestic space and water heating gas demand, for 1st January to 31st December 2015. (R^2 = 0.93).

broken stick regression using 2015 weather data (Fig. 8)[10] (gradient = 0.77, Y-intercept = −0.04). Since NDM gas demand consists of around 65% domestic and 35% non-domestic (Wilson et al., 2013), it would be expected that the NDM gas demand is higher than the domestic demand, but correlated. On average, the daily domestic gas demand calculated was 73% of the NDM gas demand for that day.

Half-hourly model predictions were compared to six weeks of EDRP data which had been reserved for validation. (This validation data included both warm and cold weather). The gradient was 0.94 and the R^2 was 0.95, showing that the model could predict the half-hourly gas consumption with good accuracy. The weekly Root Mean Squared Error (RMSE) varied from 0.10 to 0.76 kW per dwelling. The error was highest in Autumn and Spring, and lowest in Summer. The overall average RMSE from all weeks of validation was 0.34 kW per dwelling.

The UK annual domestic gas consumption was predicted by the model and was compared to official UK figures for domestic gas demand for space and water heating, and cooking, for 2003, 2010 and 2015 (BEIS, 2017b).[11] The model over-predicted for 2015 and under-predicted for 2003, and the results for 2010 were close to the actual value (Table 2). This is because the number of households[12] and boiler efficiency[13] were taken into account, but not building fabric efficiency. (All results are for the dwelling stock of 2009–2010). Since dwelling fabric efficiency has been improving between 2003 and 2015,[14] it is expected for earlier results to be under-predicted and later ones to be over-predicted. Compared to official statistics, a considerably greater proportion of domestic gas is estimated as being for DHW heating and a smaller proportion is estimated for space heating.

4. Estimating the GB half-hourly domestic heat demand for space heating and DHW

The model was used to make predictions of the half-hourly GB domestic heat demand for mild, normal and cold weather years,[15] which were taken to be weather from 2002, 2003 and 2010 respectively, as used by Sansom (2014).

Gas demand was converted to heat demand by multiplying by boiler efficiency. The mean boiler efficiency for 2009 was estimated as 80.5%, and for 2010 was 82.3% (Palmer and Cooper, 2013). Since the monitoring period covered 2009 and 2010, the mean of these was taken (81.4%) to convert the gas demand to the total heat demand and the heat demand for space heating. The efficiency was assumed not to vary with season. The DHW gas demand was converted to heat demand using an assumed efficiency of 71%. This is based on boiler efficiency being 10% lower for DHW than space heating (BRE, 2013).

The half-hourly total, DHW and space heat demand for the cold year are shown in Fig. 9, whilst Table 3 shows key results for all three years.

In general, the peak demand and maximum ramp rate of total heat demand varied relatively little between the three years, whereas the annual demand showed considerable variation. This is reflected in the load factor, which is higher for the cold year (26%) than the mild year (21%).

When heat demand is separated into space heating and DHW, it is clear that variations in space heating demand are responsible for most of the differences in heat demand between the three years.

The peak space heating demand ranged from 141 GW to 129 GW (9% lower), whereas the annual space heating demand ranged from 280 TWh to 202 TWh (28% lower). The peak demand varied a lot less than the annual demand, due to the flatter profile shape during colder weather. This is reflected in the annual load factor for space heating, which ranges from 22% in the cold year to 18% in the mild year.

There is much less variation in DHW demand due to weather. As a result, during colder years a smaller proportion of heat demand is for DHW (25%) than in a mild year (30%). The annual load factor was higher for DHW (32–33%) than space heating (18–22%).

The peak demands for space heating and DHW do not occur at the same time of day, so peaks do not add directly onto each other. Indeed, peak DHW and space heating demand may not occur on the same day. Likewise, peak demand and max ramp rate for either space heating or DHW do not necessarily occur on the same day (Table 3).

5. Comparison with previous estimates of GB heat demand

The half-hourly heat demand calculated using the model is compared to assumptions of heat demand used by Sansom (2014), Quiggin and Buswell (2016), and Eyre and Baruah (2015).

5.1. Comparison with Sansom (2014)

The half-hourly GB domestic heat demand according to Sansom (2017) and as calculated here were compared (Fig. 10). In winter, the maximum demand was lower than calculated by Sansom, and the minimum was higher.

The peak day in 2010 according to Sansom (19th December) was compared to the peak day in 2010 according to the model (20th December) (Fig. 11, bottom). The modelled peak national heat demand is considerably lower than that found by Sansom, at 170 GW rather than 277 GW. In addition, the maximum ramp rate (60 GW/hour) was half the value found by Sansom. The demand at the morning and evening peak times is lower than found by Sansom, whereas the demand in the middle of the day and at night is higher. The profile shape on the day of minimum demand in 2010 (28th June) was very similar for Sansom and for Watson et al. (Fig. 11, top).

The 2010 load duration curves produced by Sansom, and found here, were mostly similar, but there is a much greater peak according to Sansom (Fig. 12). This difference is reflected in the annual load factor, which was 16% according to Sansom and 26% according to the work here. The load factor for electricity in 2010 was 60%. Thus, although the load factor is rather higher than that found by Sansom, it is still much lower than the current electricity load factor.

Sansom found that the daily Peak Coincidence Factor (PCF) (defined in Supplementary Information, section 1.2) varied between 10% and 40%, with the PCF tending to increase as the outdoor temperature decreased. It is noted by Sansom that the monitoring period used did not contain any particularly cold weather, meaning that a higher maximum PCF could be expected in colder years. In this work the PCF ranged from around 20% during the summer, to a peak of 55% in winter.

5.2. Comparison with Quiggin and Buswell (2016)

Quiggin and Buswell produced two hourly space heating profiles: a

[10] It would have been desirable to compare EDRP data to NDM data directly, but NDM data was not available for as far back as 2009 and 2010. The average dwelling fabric efficiency may have changed between 2009 and 2015.

[11] For the three years considered the domestic gas consumption according to BEIS (2017b) was within 0.2% of the value according to the Digest of UK Energy Statistics (DUKES).

[12] Taken to be 25 million, 26 million and 27 million in 2003, 2010 and 2015 respectively (Office for National Statistics, 2017).

[13] Taken to be 72%, 82% and 82% in 2003, 2010 and 2015 respectively (Palmer and Cooper, 2013; Utley and Shorrock, 2008).

[14] The mean SAP rating of the UK housing stock increased from 47.8 in 2003 to 55.6 in 2010 and to 61.5 in 2015 (BEIS, 2017b). The SAP rating is based on a transformation of the predicted annual energy cost per floor area. Reversing this transformation, the energy cost per floor area would be expected to decline by around 14% between 2003 and 2010, and a further 11% between 2010 and 2015.

[15] These years had 2343, 1884 and 1758 degree-days respectively, on a base temperature of 15.5 °C. Changes in the number of dwellings and fabric efficiency over time are not considered – the aim is to predict what the heat demand would be for the 2010 GB housing stock under these weather conditions, not to accurately estimate what the heat demand was in those years.

Table 2
Predicted and official UK government annual domestic gas demand for 2003, 2010 and 2015, giving total gas, gas for space heating and gas for DHW (TWh).

	2003			2010			2015		
	Pred.	UK Gov.	Diff.	Pred.	UK Gov.	Diff.	Pred.	UK Gov.	Diff.
Space heating	236	306	-23%	274	313	-12%	214	249	-14%
DHW	107	72	+39%	101	69	+38%	101	43	+121%
Total	350	386	-9%	383	390	-2%	324	298	+9%

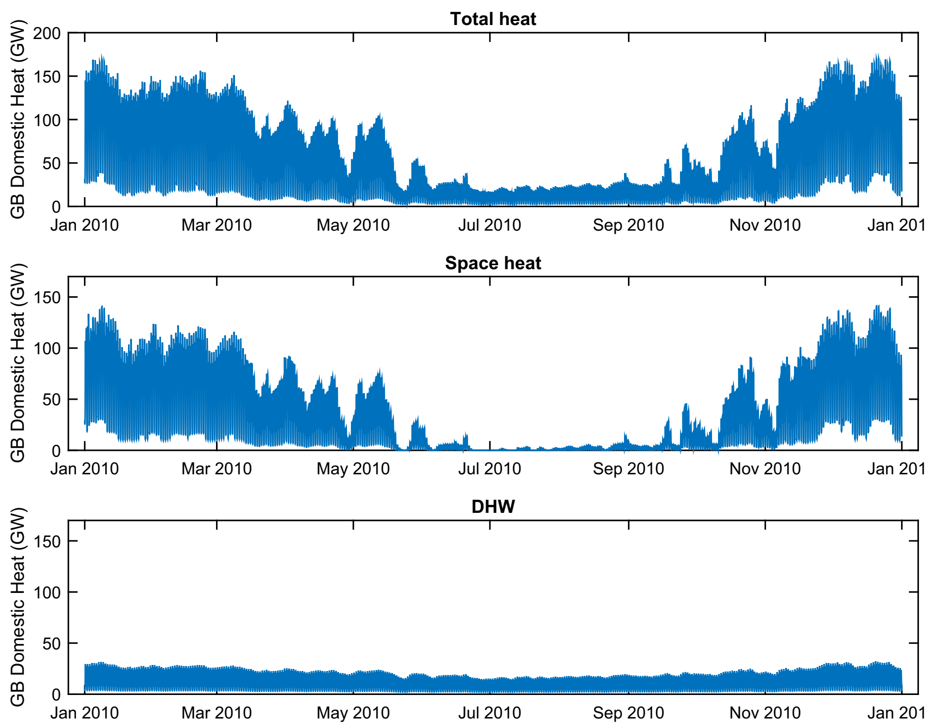

Fig. 9. Modelled GB domestic space heat and DHW heat demand for the cold weather year (2010).

Table 3
Modelled total heat, space heat and DHW demand in cold, normal and mild year.

	Year	Cold	Normal	Mild
Total heat	Annual (TWh)	391	328	309
	Peak (GW)	170	159	168
	Time and date of peak	17:30 on 20th Dec	17:30 on 18th Feb	17:30 on 1st Jan
	Max ramp rate (GW/h)	63	63	61
	Time and date of max ramp rate	07:00 on 21st Feb	07:00 on 8th Jan	07:00 on 1st Jan
	Load factor	26%	24%	21%
Space heat	Annual (TWh)	280	221	202
	Peak (GW)	141	131	129
	Time and date of peak	18:00 on 20th Dec	18:00 on 18th Feb	18:00 on 1st Jan
	Max ramp rate (GW/h)	49	48	44
	Time and date of max ramp rate	07:00 on 2nd Jan	07:00 on 18th Jan	07:00 on 5th Jan
	Load factor	22%	19%	18%
DHW	Annual (TWh)	91	87	86
	Peak (GW)	32	30	30
	Time and date of peak	07:00 on 20th Dec	07:00 on 8th Jan	07:00 on 1st Jan
	Max ramp rate (GW/h)	15	14	14
	Time and date of max ramp rate	06:00 on 20th Dec	06:00 on 8th Jan	06:00 on 1st Jan
	Load factor	32%	33%	33%
Proportion of heat demand for DHW		25%	28%	30%

"restricted" profile where occupants were constrained to a flat profile by demand side management, and an "unrestricted" profile where occupants were free to use the heating as they wished. The unrestricted profile was based on district heating measurements from a housing complex in January.

The peak domestic space heating demand when following the unrestricted profile was found to be 262 GW by Quiggin and Buswell, whereas a peak of 149 GW was found in this work. When the restricted profile was used, the peak domestic space heating demand found by Quiggin and Buswell was 117 GW. Thus, the peak demand obtained

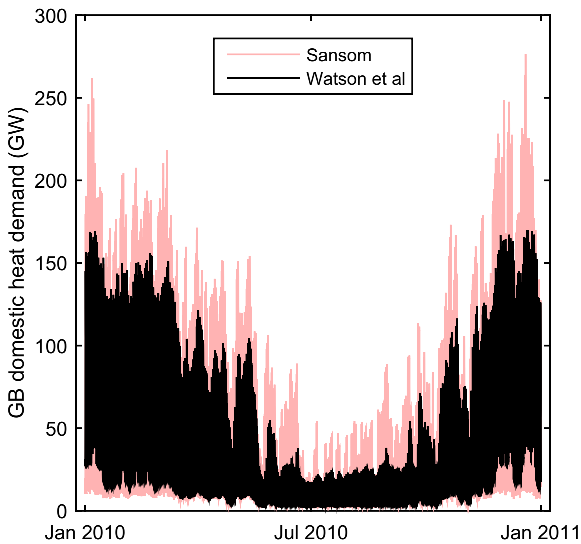

Fig. 10. Synthesised GB Domestic heat demand in 2010, according to Sansom and according to the results produced here.

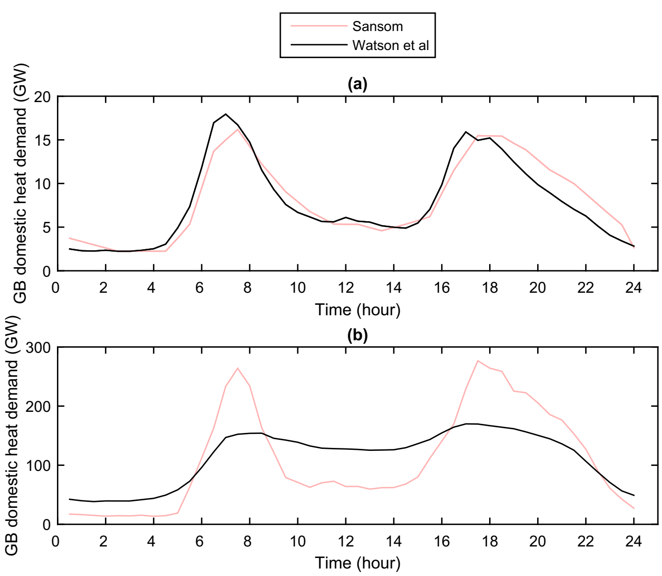

Fig. 11. Day of minimum demand (a) and maximum demand (b) in 2010, according to Sansom and according to Watson et al.

here was 27% higher than the peak demand obtained by Quiggin and Buswell for a flat daily profile, but 43% lower than when the unrestricted profile was used.

5.3. Comparison with Eyre and Baruah (2015)

Eyre and Baruah (2015) did not consider the within-day variation in demand for space heating, focusing only on seasonal variations in demand. They considered only space heating demand, not DHW heating. In the Electrification of Heat and Transport scenario by Eyre and Baruah, there was an annual electricity demand of 75 TWh from heat pumps used for space heating. This gives a peak load of 40 GW, taking into account a 20% decrease in heat pump efficiency at times of peak demand. Using the space heating profile obtained here, and taking the 20% decrease in efficiency into account, a peak demand of 47 GW is obtained when the annual demand is 75 TWh. Thus, the inclusion of sub-daily variations in space heating demand has resulted in a peak electricity demand 18% higher than found by Eyre and Baruah.

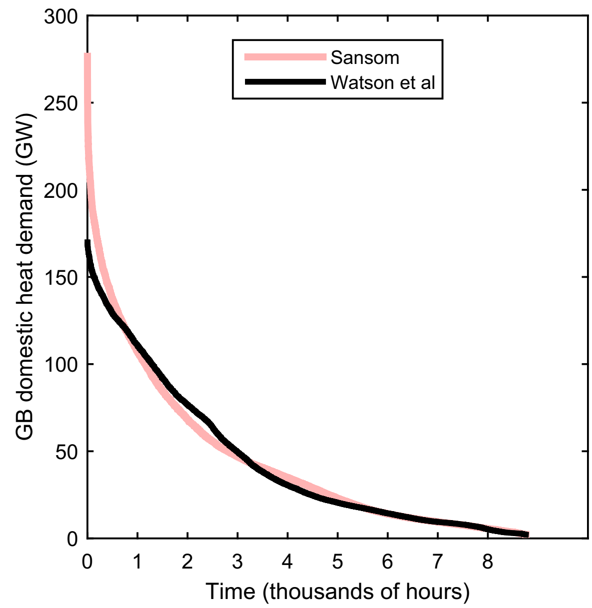

Fig. 12. Load duration curve for GB domestic heat demand for 2010, produced here and to according to Sansom.

6. Discussion

6.1. The new heat demand profiles

The profile of national heat demand obtained in this work is less “peaky” than that determined by either Quiggin and Buswell (2016) or Sansom (2014), which has important implications for the future electrification of domestic heating. Primarily, our results suggest that the national challenge of meeting peak heat demand using electricity is likely to be less severe than their profiles suggest, and which others, based on their profiles, have therefore assumed (e.g. Howard and Bengherbi, 2016). This would mean that electricity supply solutions may require less storage, either locally using batteries, or at a grid scale using batteries and other strategies, such as pumped hydro, and so become cheaper and more robust. In contrast, the peakier profiles suggested by others would favour solutions with more storage and perhaps with the retention of some heating using natural gas or other types of gas, such as hydrogen or biogas.

There are a number of reasons why the national demand profile produced here is more robust than others’ and why it differs from the one produced by Sansom. Firstly, the sample of homes from which half-hourly demands were obtained was much larger in this work, over 6000 homes, compared to Samsom's 70 or so homes. Secondly, Sansom and others, e.g. Quiggin and Buswell (2016), used the same daily heat demand profile for all days, irrespective of the ambient temperature and the socio-economic status of the households. Furthermore, Quiggin and Buswell derived profiles from heat measurements in a district heating scheme supplying just one social housing complex, meaning that the effects of social, dwelling and heating system diversity were not fully represented. In contrast, here it is shown that the winter demand profile is flatter in less affluent households, which is a result consistent with the findings of Huebner et al. (2015). More importantly, it is also shown here that the overall demand profile, after weighting by socio-economic group, is much flatter in cold weather than in milder conditions; and there are very good reasons why this is likely to be so. For example, in cold weather, people are more likely to extend the times of heating to prevent indoor temperatures dropping too low and, as the day length decreases and it becomes colder, people spend more time indoors. Also, when it is cold, boilers may be operating at full load, heat emitters producing their maximum output and thermostatic control modulating the heat output (Kane et al., 2015), thus the peak heat output is constrained by the heating system itself. This leads to the third key difference between this work and that of Sansom, which is that he used a data sample from a relatively mild weather period, and this would, our analysis suggests, lead to a peakier demand profile.

6.2. Future heat demand

Whilst the results of this work may have generated robust GB national domestic heat demand profiles, the profile may differ in the future due to: changes in heating technology leading to changes in behaviour, changes in the housing stock, changing demographics, and the warming climate. It is argued here that these factors are likely to lead to a progressive overall reduction in the peak heating demand, a reduction in the duration of the heating season, and an increase in the load factor due to the flattening of the national domestic heat demand profile.

In future, it is expected that there will be a different mix of heating technologies in British homes than at present, in particular an increased use of heat pumps and potentially heat supplied from community energy systems. Because heat pumps have a lower flow temperature and maximum heat output than gas boilers, they will inherently result in lower peaks in heat demand profiles (Love et al., 2017). Furthermore, to heat homes effectively, heat pumps are likely to be operated for longer than gas boilers and so the load may decrease less in the middle of the day. Together these effects will flatten the national demand profile, i.e. increase the load factor.

As the housing stock improves, through fabric efficiency measures and as new, more energy efficient homes, replace older homes, the national demand for heat may decrease. In particular, the heating season may become shorter due to dwellings having a lower balance temperature. However, reducing the heat loss from dwellings will reduce the peak demand, and may also reduce the energy savings to be made from intermittent, rather than continuous heating, possibly leading to an increase in continuous heating. The net effect would be a shorter heating season, with less peaky demand and possibly a higher load factor.

Changes in demographics and social habits could also change the demand for heat. Most notably, Great Britain has an aging population, which is likely to result in an increase in daytime heating because retired people tend to spend longer in their homes, especially in winter. Within the working population, there is likely to be a further increase in the extent of home working again leading to longer heating periods but, potentially, to more diversity in the timing of households' morning peak heat demand. Together, these trends will lead to a lowering of the morning peak demand and an increase in the overall heat demand load factor.

Finally, a warmer climate would be expected to reduce the annual demand for heat and shorten the heating season. With the current housing stock, heating systems and occupant behaviour regimens, this would reduce the total heat demand but also reduce the annual load factor, since the demand for heat is more "peaky" during mild weather than cold weather. By 2050, a "cold" year may resemble the results calculated for a "mild" year here.

6.3. Limitations in the EDRP data and model assumptions

There are some concerns about the reliability of EDRP data as a basis for estimating GB national heat profiles because of the age of the data, the household recruitment strategy, and the lack of explicit socio-technical data about the homes. Further, because some data needed to create the national heat demand model was not available assumptions had to be made.

The EDRP data used was from May 2009 to July 2010, around 9 years ago at the time of writing. It remains the largest and most complete publically available data set of half-hourly domestic energy demand. Since the EDRP trial of smart meters, the national roll-out has begun. As of 31st March 2018, there were a little over 4 million domestic smart meters for gas in GB (BEIS, 2018). However, the data from these is not generally available.

The way that each of the four energy suppliers recruited the households was different and the details about the process are scant. It is quite probable therefore that the sample is not completely representative of GB households. Although the availability of each household's Acorn Category enabled weighting of the sample to make it more representative of GB, this is a somewhat crude method because Acorn Categories are primarily focused on the social makeup of an area. This said, the type of dwelling does make up part of the description of many Acorn types, but because Acorn is a proprietary system, the way that different, although interrelated factors (some of which influence building energy consumption) have been combined is not known. Furthermore, Acorn type is given on a postcode level, and so it has to be implicitly assumed that the households were representative of the residents and dwellings in their postcode. Ideally, explicit information about the age, type or size of the dwellings, the characteristics of the heating system and the occupants would be available so that grossing factors to be calculated to enable reliable scaling to the national stock.

When the model is used to predict demand profiles for different years, it is implicitly assumed that the relative number of homes in each Acorn category stays approximately the same year on year, as does the proportion of homes in each LDZ. Both are reasonable assumptions, at least for the limited span of years studied in this paper (2002–2015). It is also assumed that in GB as a whole, households use the same profile as the EDRP households, even when they have other forms of heating, i.e. not gas central heating. This assumption is reasonable, because in 2010, 83% of GB homes had gas central heating (Palmer and Cooper, 2013) and a further 4% had oil central heating, which is likely to be used in a similar manner to gas heating. Although a limited number of gas demand profiles were used, one for each 3 °C effective air temperature band, this is unlikely to have introduced much error, compared to the other sources of uncertainty, but refinements could be a subject of future work.

A development beyond Sansom's work was the separation of the gas demand into that for space heating and that for DHW. In future, separate systems may be used to provide DHW and space heating. Here DHW heat demand was calculated to be 25% of the annual GB total demand in 2010, whereas according to BEIS (2017b), 18% of domestic heat demand in 2010 was for DHW. Both figures are however based on modelling rather than measurement, so it is difficult to know which, if either, is correct. The BEIS figures are based on the predictions of the Cambridge Housing Model, whilst here an empirical model assumed that all gas used at outdoor temperatures above 18 °C was for DHW (once cooking had been removed). It is of course possible that some space heating occurred at these temperatures and that this has been misinterpreted as DHW demand. Furthermore, the same mean daily effective outdoor air temperature was used for estimating variations in DHW heat demand as was used for total heat demand. In reality the cold-water inlet temperature reacts slowly to changes in outdoor air temperature and may never get as cold. These effects may lead to a small overestimate of the DHW heat demand. In future work it might be better to use a different effective temperature with a different smoothing coefficient (α) for DHW energy demand predictions.

Whilst gas, or electricity, demand is relatively easy to measure, the actual heat demand is very difficult to determine. An assumption therefore has to be made about the efficiency of energy to heat conversion, and this introduces uncertainty in all approaches to heat demand profile prediction, whether based on thermal modelling or field measurement. Assumptions that use fixed values do not alter the demand profile for the DHW and space heating components, though the relative values will affect the combined profile. In practice, the efficiency of gas boilers tends to increase with heat demand and this will tend to flatten the daily heat demand profile. Further work on this matter may be worthwhile.

6.4. Total national heat demand for buildings

The work reported here is necessary, largely because the sub-daily national heat demand for dwellings is unknown. The Non-Daily Metered, daily gas demand is available, but this combines both dwelling and small-non domestic gas demand, and is not half-hourly. In his work, Sansom assumed that commercial heat demand followed the same profile as domestic micro-CHP, whereas Quiggin and Buswell assumed that the demand for non-domestic heat was flat.

It is worth speculating about the total heat demand profile of the entire national building stock, i.e. the combined domestic and non-domestic stock.

Whilst domestic buildings have a relatively small volume-to-surface area ratio and a limited range of heating system types and occupant behaviours, the non-domestic stock is very different, and this has consequences for their energy demand. Most importantly, non-domestic buildings tend to be larger and so the space heating demand is less influenced by the ambient temperature. The heat gains from occupants, lighting, computers etc. are also higher, which further reduces the impact of ambient temperature on demand. The occupancy patterns are also much more diverse as are types of heating (and ventilation) system type used. Consequently, the timing of peak heat demands is also likely to be more diverse, with some non-domestic buildings being heated 24 h per day. Overall, therefore, whilst the total heat demand of the national building stock, i.e. including both domestic and non-domestic buildings, will be greater, the overall profile of heat demand will be flatter, i.e. a higher load factor, than for dwellings alone. The load profile flattening achieved by combining domestic and non-domestic buildings is, of course, well known and important to the design of district heat networks (Arup, 2011).

6.5. International relevance

Great Britain is not alone in having an oceanic climate, being largely dependent on fossil fuels for heating, and seeking to substantially reduce greenhouse gas emissions. The electrification of heating, combined with an increase in renewable electricity generation, is a widespread policy prescription for reducing emissions from domestic heat. Therefore, obtaining more accurate, higher resolution predictions of heat demand than were hitherto necessary may be an important task for many other countries in the coming years.

The results calculated here are, of course, specific to GB. However, there are several recommendations that can be made when obtaining estimates of national half-hourly heat demand for other countries. Firstly, a data-driven approach is appropriate when estimating national demand (as opposed to thermal modelling for example), due to the importance of diversity between households in determining peak demand. Secondly, it is necessary to have a large sample in order to fully include the effects of diversity. Thirdly, it is important for the monitoring period to include the full range of weather which is commonly experienced in a country. Fourthly, it is important to include the variation in profile shape that occurs with outdoor temperature, otherwise peaks will be overestimated.

The exact profile shape and how it varies with outdoor temperature is likely to be specific to each country, influenced by a mixture of social practices, dwelling stock, climate and heating system.

Domestic smart meters are being rolled out across Europe and beyond and could transform the insights we have about national heat profiles, enabling the tracking of changes to this profile as, for example, improvements are made to dwelling fabric efficiency and changes to the way homes are heated are introduced. The methods outlined in this paper can be used internationally to will help those undertaking such analyses.

7. Conclusion and policy implications

Using half-hourly gas demand data collected in 2009–10, via smart meters installed in over 6000 homes in Great Britain (GB), a model has been constructed which allowed the half-hourly national domestic heat demand for space heating and domestic hot water to be predicted. The model takes account of the impact on daily heat demand of the daily outdoor air temperature and effects of the socio-economic status of households and ambient temperature on daily half-hourly demand profiles. These characteristics set the model apart from those previously developed to estimate national domestic heat demand.

Compared to previous national heat models, the model presented here was developed from a much larger sample of dwellings, monitored at half-hourly intervals for a much longer period. This enabled the variation in demand profile with temperature and household type to be more rigorously modelled.

Previous researchers have used the same, peaky, load profile for all ambient temperatures. It is shown here that the profile on cold days was much flatter than they have suggested and so the predicted peak heat demand is much less than previously estimated.

The reliability of the model is demonstrated. The predicted national daily gas demand was highly correlated with the measured daily demand for the same period as the measurements, and the total annual gas demand was within 2% of the value produced by the UK government. The predicted gas demand for heating domestic hot water was greater than the government's calculated value and the demand for space heating correspondingly lower.

The predicted peak GB half-hourly domestic heat demand ranged from 159 GW to 170 GW depending on the annual ambient temperature, and the peak demand for space heating alone ranged from 135 to 148 GW. The maximum rate of change of demand, the ramp rate, was 60 GW/h. The peak demand and maximum ramp rate are respectively 40% and 50% less than the values produced by Sansom, which have been widely used for informing future GB and UK domestic heating scenarios.

The model's predictions, together with considerations of the way in which the housing stock will evolve, changes to heating technology, and changes in the UK demographic, could have far-reaching implications. In particular, the work here suggest that peak heat demand and maximum ramp rate have been very substantially overestimated, leading to overly pessimistic assessments of the prospects for electric heating (e.g. Howard and Bengherbi, 2016). A shift towards heating GB's homes using electricity, rather than natural gas, will therefore put much less pressure on the electricity supply system than previously anticipated. Nevertheless, the electrification of heating remains a significant challenge, and is likely to result in considerably greater peaks in electricity demand and seasonal variation than at present.

A recent UK government policy document on decarbonisation (BEIS, 2017a) states that it is uncertain which combination of low-carbon heating technologies will work best at scale. The development of more accurate estimates of half-hourly domestic heat demand is a key step in determining a cost-effective solution for decarbonising UK domestic heat demand and clarifying this uncertainty. The model presented here offers this greater accuracy.

As an aid to future scenario modelling, the profiles produced in this work are freely available at Watson et al. (2018).

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References

Acorn, 2014. The Acorn User Guide. Available at: 〈https://acorn.caci.co.uk/downloads/Acorn-User-guide.pdf〉 (Accessed 8 February 2018).

AECOM Building Engineering, 2014. Energy Demand Research Project: Early Smart Meter Trials, 2007–2010. [data collection]. UK Data Service. SN: 7591. Available at: http://doi.org/10.5255/UKDA-SN-7591-1 (Accessed 24 June 2016).

Arup, 2011. Decentralised Energy Masterplanning – A Manual for Local Authorities. Ove Arup and Partners Ltd, London.

Barton, J., et al., 2013. The evolution of electricity demand and the role for demand side participation, in buildings and transport. Energy Policy 52, 85–102. https://doi.org/10.1016/j.enpol.2012.08.040.

BEIS, 2017a. The Clean Growth Strategy – Leading the Way to a Low Carbon Future. Department for Business, Energy and Industrial Strategy, London (Available at). 〈https://www.gov.uk/government/publications/clean-growth-strategy〉.

BEIS, 2017b. Energy Consumption in the UK. Department for Business, Energy and Industrial Strategy. London. Available at: 〈https://www.gov.uk/government/statistics/energy-consumption-in-the-uk〉 (Accessed 6 November 2017).

BEIS, 2018. Smart Meters Quarterly Report to end March 2018 Great Britain. Department for Business, Energy and Industrial Strategy. London. Available at: 〈https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/712151/2018_Q1_Smart_Meters_Report_.pdf〉 (Accessed 12 October 2018).

BRE, 2013. SAP 2012 – The Government's Standard Assessment Procedure for Energy Rating of Dwellings. Building Research Establishment, Watford, on behalf of Department of Energy and Climate Change.

Carbon Trust, 2017. Degree Days. Available at: 〈https://www.carbontrust.com/resources/guides/energy-efficiency/degree-days/〉 (Accessed 14 December 2017).

Chaudry, M., et al., 2015. Uncertainties in decarbonising heat in the UK. Energy Policy 87, 623–640. (Available at). 〈http://linkinghub.elsevier.com/retrieve/pii/S0301421515300306〉.

DECC, 2012. The Future of Heating: A Strategic Framework for Low Carbon Heat in the UK. Department of Energy and Climate Change, London (Available at). 〈https://www.gov.uk/government/publications/the-future-of-heating-a-strategic-framework-for-low-carbon-heat〉.

Energy Technologies Institute, 2015. Smart Systems and Heat: Decarbonising Heat for UK Homes. Birmingham. Available at: 〈http://www.eti.co.uk/wp-content/uploads/2015/03/Smart-Systems-and-Heat-Decarbonising-Heat-for-UK-Homes-.pdf〉.

Eyre, N., Baruah, P., 2015. Uncertainties in future energy demand in UK residential heating. Energy Policy 87, 1–13. https://doi.org/10.1016/j.enpol.2014.12.030.

Hawkins, D.M., 1976. Point estimation of the parameters of piecewise regression models. J. R. Stat. Soc. Ser. C. (Appl. Stat.) 25 (1), 51–57.

Heller, A.J., 2002. Heat-load modelling for large systems. Appl. Energy 72 (1), 371–387. (Available at). 〈http://linkinghub.elsevier.com/retrieve/pii/S030626190200020X〉.

Howard, R., Bengherbi, Z., 2016. Too Hot to Handle? How to Decarbonise Domestic Heating. Policy Exchange, London. Available at: 〈https://policyexchange.org.uk/publication/too-hot-to-handle/〉.

Huebner, G.M., et al., 2015. The shape of warmth: temperature profiles in living rooms. Build. Res. Inf. 70, 298–305. https://doi.org/10.1080/09613218.2014.922339.

Kane, T., Firth, S.K., Lomas, K.J., 2015. How are UK homes heated? A city-wide, socio-technical survey and implications for energy modelling. Energy Build. 86, 817–832. (Available at). 〈http://linkinghub.elsevier.com/retrieve/pii/S0378778814008317〉.

Leveque, F., Robertson, A., 2014. Pathways for Heat: Low Carbon Heat for Buildings. Carbon Connect, London.

Love, J., et al., 2017. The addition of heat pump electricity load profiles to GB electricity demand: evidence from a heat pump field trial. Appl. Energy 204, 332–342. https://doi.org/10.1016/j.apenergy.2017.07.026.

Maclean, K., et al., 2015. Energy System Crossroads - Time for Decisions. Imperial College London.

National Grid Data ItemExplorer, No Date. Available at: 〈http://mip-prod-web.azurewebsites.net/DataItemExplorer/Index〉(Accessed 19 January 2017).

Office for National Statistics, 2017. Families and households. Available at: 〈https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/families/datasets/familiesandhouseholdsfamiliesandhouseholds〉. (Accessed 29 June 2018).

Palmer, J., Cooper, I., 2013. United Kingdom Housing Energy Fact File. Department of Energy and Climate Change, London.

Pedersen, L., Stang, J., Ulseth, R., 2008. Load prediction method for heat and electricity demand in buildings for the purpose of planning for mixed energy distribution systems. Energy Build. 40 (7), 1124–1134. (Available at). 〈http://www.sciencedirect.com/science/article/pii/S0378778807002381%5Cnhttp://www.sciencedirect.com.prx.library.gatech.edu/science/article/pii/S0378778807002381〉.

Quiggin, D., 2014. Modelling the Expected Participation of Future Smart Households in Demand Side Management, Within Published Energy Scenarios (Ph.D. thesis). Loughborough University, pp. 160–161.

Quiggin, D., Buswell, R., 2016. The implications of heat electrification on national electrical supply-demand balance under published 2050 energy scenarios. Energy 98, 253–270. https://doi.org/10.1016/j.energy.2015.11.060.

Raw, G., Ross, D., Cripps, A., 2011. Energy Demand Research Project: Final Analysis. AECOM (on behalf of Department of Energy and Climate Change), St Albans.

Sansom, R., 2014. Decarbonising Low Grade Heat for a Low Carbon Future (Ph.D. thesis). Imperial College London, pp. 59–81.

Sansom, R., Strbac, G., 2012. The impact of future heat demand pathways on the economics of low carbon heating systems. In: Proceedings of the BIEE – 9th Academic Conference. Available at: 〈http://www.biee.org/downloads/the-impact-of-future-heat-demand-pathways-on-the-economics-of-low-carbon-heating-systems/〉.

Sansom R., 2017. Personal communication, November 2017.

Utley and Shorrock, 2008. Domestic Energy Fact File. Building Research Establishment, Watford, on behalf of Department of Energy and Climate Change.

Watson, S., Lomas, K.J., Buswell, R., 2018. Data cleaning, temperature and gas demand weighting, and determining the DHW demand (Available at). Suppl. Inf. https://doi.org/10.17028/rd.lboro.6795395.

Wilson, I.A.G., et al., 2013. Historical daily gas and electrical energy flows through Great Britain's transmission networks and the decarbonisation of domestic heat. Energy Policy 61, 301–305. (Available at). 〈http://linkinghub.elsevier.com/retrieve/pii/S0301421513004655〉.